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**PERFORMANCE OF A CATALYTIC REACTOR AT SIMULATED
GAS TURBINE COMBUSTOR OPERATING CONDITIONS**

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SUMMARY

The performance of a catalytic reactor 12 cm in diameter and 17 cm long was evaluated at simulated gas turbine combustor operating conditions. Inlet temperatures of 600 and 800 K, pressures of 3 and 6 atm, and reference velocities of 9 to 30 m/s were tested. The propane fuel was premixed with air. Data were taken for equivalence ratios as high as 0.43. Measurements were made of pressure drop, exit temperature, and emissions of nitrogen oxides, carbon monoxide, and unburned hydrocarbons.

The combustor pressure loss was about 4 percent of the upstream total pressure at a reference velocity of 23 m/s.

For lean fuel-air ratios reaction continued even for combustor temperature rises of only a few degrees; however, efficiency was poor until the exit temperature was at least 1400 K; for some conditions, exit temperatures as high as 1600 K were required for good efficiency. Once the efficient operating range had been reached, emissions of unburned hydrocarbons decreased to less than 4×10^{-3} g $\text{CH}_{2.67}$ /kg fuel, carbon monoxide emissions generally dropped to less than 1 g CO/kg fuel, and total nitrogen oxides were about two orders of magnitude below current-combustor values (less than 0.1 g NO_2 /kg fuel).

Within the efficient operating range, the variation in exit temperature from the hottest to the coldest locations was less than 10 percent of the average temperature rise across the reactor.

INTRODUCTION

A catalytic reactor was tested to determine its feasibility for use as a gas turbine combustor and to determine its potential for low emissions.

Pollutant emissions from gas turbine engines have become one of the major interests of combustor designers. Three of the most important pollutants resulting from hydrocarbon/air combustion are unburned hydrocarbons, carbon monoxide, and nitrogen oxides. The first two are primarily products of incomplete combustion for the lean overall fuel-air ratios typical of gas turbine operation; they represent inefficiency. In contrast, nitrogen oxides are formed in concentrations exponentially dependent on flame temperature in any combustion process which includes nitrogen; they cannot be removed simply by improving the combustion efficiency.

In a combustor having a non-uniform distribution of fuel-air ratio throughout the primary zone, the production of nitrogen oxides is not strongly dependent on mean primary zone fuel-air ratio (refs. 1 and 2). Because current production gas turbine combustors operate with a non-uniform primary zone it is difficult to obtain significant reductions in emissions of nitrogen oxides without a sacrifice in combustion efficiency unless the fuel-air mixing is improved. It has been shown (ref. 3) that the concentration of nitric oxide can be significantly reduced from present levels while maintaining near 100 percent combustion efficiency by operating with a lean premixed, prevaporized combustor primary zone. Unfortunately, a premixed combustor does not have as wide a range of combustion stability as a conventional, poorly mixed, combustor; in fact, the blow-out point for a premixed system is near the lean flammability limit for the fuel used, while in a non-uniform system local rich zones can sustain burning even when the mean fuel-air ratio is below the lean flammability limit.

For a given set of conditions, a catalyzed reaction occurs at a faster rate than that in a flame because of a reduction in the activation energy of

the reaction (ref. 4). As a result, one advantage of a premixed-catalytic combustor compared with a premixed-flame combustor is the ability to operate below the lean flammability limit to give reduced nitrogen oxides emissions.

Successful reaction in a catalytic combustor requires the reactants to undergo the following series of processes (refs. 4 and 5):

- (1) The reactants must diffuse to the catalytic surface.
- (2) At least one of the reactants must be chemically adsorbed onto active surface sites.
- (3) Reaction can now occur.
- (4) Desorption of the products must take place.
- (5) The products have to diffuse back into the main gas stream.

Although the catalyst increases the rate of step (3) over that in a flame system, the rate of one or more of the other steps necessary to catalytic combustion may be enough lower than rate (3) that it controls the overall rate of combustion. In general, adsorption is extremely fast (ref. 4) so that frequently only diffusion and chemical reaction are considered as possible rate-limiting steps (refs. 6 and 7).

Many metals and metal oxides are capable of acting as catalysts for oxidation reactions; however, at the high temperatures necessary for oxidation few metals, except the noble metals, resist oxidation themselves (ref. 4). The relative catalytic activities of a number of metal oxides and metals have been determined for the oxidation of methane (ref. 8) and of C_5 and C_6 hydrocarbons (ref. 9). These studies showed that:

- (1) Each fuel may be oxidized most rapidly by a different catalyst, although, in general, platinum was the most active catalyst per unit weight.
- (2) Some metal oxides are more active catalytically when supported on alumina; others are more active when unsupported.
- (3) For highest activity, the best method of impregnation of the catalyst on the alumina support may not be the same for all catalysts.

(4) Paraffins are the most difficult fuels to oxidize catalytically; methane is the most difficult paraffin to oxidize and ease of oxidation increases with carbon number in this series.

It has been noted that adsorption of at least one of the reactants onto active sites of the catalyst must take place before reaction can occur. Some substances are more strongly adsorbed than others; they act as poisons by filling the active sites thereby preventing the adsorption of the reactants (ref. 4). Lead and sulfur compounds can be catalyst poisons for the oxidation of hydrocarbons.

Catalytic combustion has been studied at several laboratories because of its potential for efficient, ultra-lean, low NO_x energy release. Applications being considered include stationary power systems, and automotive and aircraft gas turbine engines.

Blazowski and Bresowar recently tested a catalytic reactor primary zone using JP-4 fuel (ref. 10). They found that total nitrogen oxides (NO_x) emitted were less than 2 ppm at 650 K inlet temperature and a fuel-air ratio of 0.03. At a reference velocity of 20 m/s, pressure drop through the monolith bed was 2 percent of the upstream total pressure. They measured a combustion efficiency of virtually 100 percent for primary zone fuel-air ratios between 0.02 and 0.03, but found that efficiency fell off sharply when fuel-air ratio was reduced below 0.02.

For the present study a single proprietary 12-cm diameter catalytic reactor manufactured by Engelhard Industries was tested over a range of conditions applicable to gas turbine engines. The tests simulated combustor primary zone operation. No attempt was made to determine the effects of changes in the catalyst or substrate material or method of manufacture on the results. Table I presents the test conditions. Inlet-air temperature was varied from 600 to 800 K; inlet-air pressure was maintained at either 3 or 6 atm; the reference velocity covered a range from 9 to 30 m/s; and equivalence ratios ϕ as high as 0.43 were tested. Gaseous propane fuel was used. Measurements were made of pressure drop, exit temperature, and emissions of nitrogen oxides, carbon monoxide, carbon dioxide, and unburned hydrocarbons.

APPARATUS AND INSTRUMENTATION

General Description

Details of the apparatus are shown in figure 1. The facility consists of a 10-cm diameter duct to which cylindrical sections housing inlet instrumentation, the test burner and exit instrumentation are attached. Following these is a water quench system for cooling the combustion gases.

Air System

This facility is connected to the laboratory combustion air supply. An indirectly-fired heat exchanger was used to preheat the air. The combustor airflow rate was measured using an ASME standard orifice. Downstream of the facility shown in figure 1 a back-pressure valve was installed which permitted the test section to be pressurized to from 1 to 7 atm.

The inlet duct was insulated to minimize inlet temperature non-uniformities. Measurements of the inlet temperature with the 12-thermocouple instrumentation section of figure 1(b) installed in the inlet duct showed that there was less than 40 K difference between the coldest and hottest points with an 830 K inlet temperature.

Fuel System

Commercial grade (92 percent pure) gaseous propane was used for all tests (see table II). Propane has a heating value near that of jet aircraft fuels so that combustion characteristics, especially NO production, are similar. By using a gaseous fuel, problems associated with atomization were avoided and it was possible to simulate a prevaporized as well as a premixed system.

The propane was supplied and stored as a liquid, then superheated to 370 K at 10 atmospheres to insure complete vaporization before metering the flow. The flow was measured with an ASME standard orifice.

The fuel was introduced through a fuel tube located about 2 m upstream of the test combustor to allow sufficient time for thorough mixing of fuel and air. A small swirler was located on the end of the fuel tube to give some initial mixing, as shown in figure 1(a).

Reactor

The catalyst bed was a monolithic structure as shown in figure 2. The bed diameter was 12.1 cm and the length was 17 cm. The reactor housing was made of Inconel 601. The walls were insulated to avoid temperature gradients.

Instrumentation

Rakes for inlet instrumentation were avoided to minimize the possibility of burning upstream of the combustor. Static pressure was measured at the wall and two Chromel-Alumel thermocouples were inserted to depths of 1 cm and 2 cm, respectively, from the wall of the inlet section. Isothermal tests with the 12-thermocouple instrumentation section of figure 1(b) located at the inlet showed that at a depth of 1 cm from the wall the temperature was slightly less than the average inlet temperature and at 2 cm from the wall the temperature was slightly higher than the average. The average inlet temperature for tests using the 2-thermocouple instrumentation section, then, were determined from the numerical average of the readings from these two thermocouples. The two thermocouples usually read within 5 K of each other and never disagreed by more than 10 K.

Details of the exit instrumentation are shown in figure 1(b). A single wall static pressure tap was provided. Twelve platinum/platinum-13-percent-rhodium thermocouples were arranged in the pattern shown to sample on centers of equal area. A single-point gas-sampling probe was used which could be traversed to sample at any position along a diameter; however, after a few tests showed that there was little variation in emissions along the traversed diameter, data were subsequently taken with the probe at the center-line position only. The probe was made of stainless steel and was water cooled.

Stainless steel tubing of 0.95 cm diameter connected the gas sample probe with the exhaust gas analyzers. To prevent condensation of unburned hydrocarbons this sample line tubing was heated by electrical tracing to maintain the sample gas temperature between 410 and 450 K. The sample line was approximately 18 m long.

Gas analysis equipment included a Beckman Flame Ionization Detector for measuring unburned hydrocarbons, Beckman nondispersive infrared analyzers for measuring concentrations of carbon monoxide and carbon dioxide, and a Thermo-Electron Chemiluminescent instrument for nitric oxide concentration.

After each change in conditions a delay of 3 to 5 minutes was allowed for stabilization before taking data. All the millivolt signals from pressure transducers, thermocouples, and gas analysis equipment for each test point could be recorded in less than 3 seconds by the automatic data system used.

COMPUTATIONS

Reference Velocity

The reference velocity is defined as the velocity based on combustor inlet conditions and maximum combustor cross-sectional area; for this report, the cross-sectional area used was determined from the inside diameter of the housing, 12.1 cm, without any allowance for area reduction

due to the bed structure. The actual inlet velocity in each of the channels of the combustor would be 1.23 times the reference velocity.

Equivalence Ratio

The equivalence ratio ϕ is defined as the fuel-air ratio divided by the stoichiometric fuel-air ratio. For propane, the stoichiometric fuel-air ratio is 0.064 g fuel/g air.

Equivalence ratios at each test point were determined in two ways. First, a direct determination was made from the measured flowrates of fuel and air. A second equivalence ratio was calculated from a carbon balance using the measured concentrations of carbon monoxide, carbon dioxide, and unburned hydrocarbons according to the following expression (ref. 11):

$$\phi = \frac{(C_{\text{CO}} + C_{\text{CO}_2} + C_{\text{HC}}) M_f \times 10^{-6}}{0.064 M_p n_C \left\{ 1 - \frac{1}{2} \left[\frac{1}{2} r (C_{\text{CO}} + C_{\text{CO}_2}) \times 10^{-6} + C_{\text{CO}} \times 10^{-6} \right] \right\}}$$

where

C_x concentration of constituent x in ppmv

M_f molecular weight of fuel

M_p molecular weight of products of combustion

n_C number of atoms of carbon in one molecule of fuel

r hydrogen-to-carbon atom ratio in fuel molecule

The data in this report is presented as a function of the equivalence ratio based on fuel and air flow measurements.

Emission Index

It has become conventional to report emissions in units of g pollutant/kg fuel. This emission index permits direct comparison of emissions measured in a combustor primary zone with those resulting after dilution with secondary air.

The emission indexes for this report were determined from the following formula:

$$E.I._x = \frac{M_x (1 + f)}{M_p f} \times 10^{-3} C_x$$

where f is the fuel-air ratio based on the carbon balance. The molecular weights M_x used in this calculation were as follows: CO: 28.01; CO₂: 44.01; nitrogen oxides, NO_x: 46.01; unburned hydrocarbons: 14.68; products of combustion: 28.97.

It is conventional to report nitrogen oxides emissions as equivalent NO₂ (molecular weight, 46.01). Note also that the unburned hydrocarbons has been assumed to be CH_{2.67}, which has the same hydrogen-carbon atom ratio as propane.

Combustion Efficiency

The combustion efficiency was computed both from the gas analysis measurements and from thermocouple data.

For complete combustion all species must attain their equilibrium concentrations. In particular, unburned hydrocarbons and carbon monoxide must reach equilibrium values in order that the full heating value of the fuel be released; lack of equilibrium for the other species contributes negligibly to inefficiency. The combustion efficiency is

$$\eta = 1 - E.I._{CH_{2.67}} \times 10^{-3} - 0.227(E.I._{CO} - E.I._{eqCO}) \times 10^{-3}$$

where the $E.I._x$ are the emission indexes of constituent x and $E.I._{eq}$ is the emission index based on the equilibrium concentration. The equilibrium concentration of unburned hydrocarbons is negligible except for equivalence ratios greater than 1; therefore $E.I._{eqCH_{2.67}}$ is not included in the efficiency calculation.

The thermocouple data were used to compute a combustion efficiency according to the following simplified expression:

$$\eta = \frac{(T_{\text{exit, average}} - T_{\text{inlet, average}})_{\text{measured}}}{(T_{\text{exit}} - T_{\text{inlet}})_{\text{ideal}}}$$

PRELIMINARY TESTS

Fuel Presentation

To determine if the fuel-air ratio distribution at the combustor inlet was uniform, the exit instrumentation section, containing the traversing gas sampling probe, was installed upstream of a mock-up of the catalytic reactor. Propane was introduced through the fuel tube to give concentrations of 700 and 2 000 ppm at inlet-air temperatures of 600 and 700 K and pressures of 3 and 6 atm. This unburned fuel concentration was measured with the Flame Ionization Detector (FID). No detectable concentration differences were evident as the probe traversed across the inlet plane for either fuel concentration.

Pressure Loss

Figure 3 gives the results of measurements of the pressure loss across the catalytic reactor for both isothermal (no fuel flow) and reacting conditions. Although only static pressures were measured, the

difference between static and total pressure is slight at the test conditions. For example, at a reference velocity of 30 m/s, the difference between static and total pressure is only 2.3 percent for an inlet temperature of 600 K.

At 30 m/s, the maximum reference velocity tested with reaction, the pressure loss was nearly 7 percent of the upstream pressure, while a loss of about 4 percent was obtained at a reference velocity of 23 m/s.

RESULTS AND DISCUSSION

Ignition Characteristics

For inlet-air temperatures of 700 K or greater, an immediate exit temperature rise was evident from the reactor even for fuel flows too low to be measured; temperature rises as little as 25 K were observed. Tests showed that an inlet-air temperature of 600 K was not sufficient for starting the combustor. However, once reaction had been initiated with an inlet temperature of 700 K, it was possible to reduce the inlet temperature to 600 K without loss of combustion. No tests were made to determine the minimum inlet-air temperature for ignition, nor was there any attempt to determine if it was possible to extinguish the reaction by reducing the inlet temperature below 600 K.

Upstream Burning

A problem anticipated with premixed combustion systems is that of burning in the inlet duct upstream of the combustor. In the present tests upstream burning off the inlet thermocouples was encountered for inlet-air temperatures of 700 K or greater, reference velocities less than 15 m/s and equivalence ratios greater than 0.34 to 0.4 for both 3 atm and 6 atm inlet pressure. When upstream burning occurred, fuel flow was reduced until the flame seated on the thermocouples blew out.

No upstream burning occurred during the recording of the data presented in this report.

Gas Sample Validity

Although a traversing gas sampling probe was used, most data were taken at a fixed center line position. To check the validity of this single-point data a comparison was made between the equivalence ratio determined from fuel and air flow measurements and one using a carbon balance from the emission measurements. This comparison is shown in figure 4. To insure representative sampling, these values should be within ± 15 percent (see ref. 11) which they are for most of the data.

For the very inefficient operating conditions, levels of unburned hydrocarbons were higher than it was possible to measure with the Flame Ionization Detector. Carbon balances in such cases were meaningless. In general, these data are not reported here; however, borderline points which helped to show trends in the CO concentrations or temperatures were included even though a meaningful validity check could not be made. These points are flagged in figure 4.

Combustion Efficiency

The combustion efficiency can be computed from the difference between the measured and equilibrium concentrations of unburned hydrocarbons and carbon monoxide. The results of this computation are given in figure 5.

Although the combustion reactions could be initiated at very low fuel-air ratios, efficiency was low. As the equivalence ratio was increased, a critical value was reached at which the efficiency began to rise rapidly, reaching 100 percent after only a small further increase in equivalence ratio. This critical value of equivalence ratio is

dependent on inlet temperature, inlet pressure, and reference velocity.

An alternate way to determine combustion efficiency is to measure the exit and inlet temperatures. Combustion efficiencies computed from thermocouple data were consistently about 3 to 7 percent lower than those based on gas analysis. The combustor exit temperature response is given in figure 6, with the average exit temperature plotted against equivalence ratio. The thermocouple readings were not corrected for radiation or conduction errors.

As expected from the efficiency curves of figure 5, the exit temperature is well below the ideal for low equivalence ratios and rises rapidly after a critical value of equivalence ratio has been reached.

Emissions

Oxides of Nitrogen

Total NO_x emissions (nitric oxide, NO , plus nitrogen dioxide, NO_2) were measured to be less than 0.5 ppm for all conditions tested. The emission index was always less than 0.1 g NO_2 /kg fuel. The chemiluminescent analyzer was calibrated with a 120-ppm calibration gas. Because no lower concentration of calibration gas was available it was not possible to calibrate the analyzer ranges used in these measurements; the measured concentrations may therefore be inaccurate. However, even allowing for the possibility of considerable inaccuracy, these results show that the total nitrogen oxides emissions are lower than result from conventional gas turbine combustors by about two orders of magnitude.

Carbon Monoxide

Figure 7 gives the typical carbon monoxide emission response to changes in equivalence ratio. For very lean mixtures very little CO is produced; this result is not due to high efficiency operation, but rather indicates that only a small fraction of the fuel is burned. As the equivalence ratio is increased the production of CO begins to increase as a greater percentage of the fuel is reacted. Over a narrow range of equivalence ratio the CO concentration reaches a peak value then rapidly drops as the combustion efficiency approaches 100 percent. With the exception of figure 7, all the data presented in this report are for fuel-air mixtures richer than the value which produces the peak carbon monoxide concentration.

Figure 8 shows the carbon monoxide emissions recorded for the various inlet conditions. As equivalence ratio is increased, carbon monoxide concentration decreases. In most cases emissions of less than 1 g CO/kg fuel were achieved. However, as shown in figure 8(d), with 800 K inlet temperature and 3 atm pressure, the CO concentration appears to level off just above 1 g CO/kg fuel. This result may be due to insufficient residence time as the reference velocities were the highest tested.

The effect of reference velocity can be seen by cross plotting some of the results of figure 8. This is done in figure 9 for 800 K inlet temperature. For tests with the 6-atm inlet pressure reference velocity had a dramatic effect on CO emissions for equivalence ratio less than 0.3; the CO concentrations were reduced by two orders of magnitude by decreasing reference velocity from 18 to 13 m/s.

The 3-atm data shows effects similar to those seen in the 6-atm case, but it is possible to reach higher reference velocities before performance deteriorates. If the abscissa had been mass flow per unit area, the 6-atm curves would lie slightly to the right of the 3-atm, indicating that for constant mass flow, performance improves with pressure.

Unburned Hydrocarbons

The effect of equivalence ratio on the emissions of unburned hydrocarbons shown in figure 10 is the same as exhibited for carbon monoxide. As equivalence ratio is increased the emission index of unburned hydrocarbons continues to decrease until concentrations too small to be measured by the Flame Ionization Detector are reached. It was estimated that a minimum measurable concentration would be about 0.05 ppm; for an equivalence ratio of 0.3 this concentration converts to an emission index of $4 \times 10^{-3} \text{ g CH}_{2.67}/\text{kg fuel}$. For cases in which the concentration was measured to be less than 0.5 ppm, the emission index was calculated from 0.05 ppm.

A cross plot of the 800 K results is presented in figure 11 to show the effect of reference velocity. Trends are similar to those for CO.

Exit Temperature Uniformity

A measure of the uniformity of the exit temperature is the difference between maximum and minimum exit temperatures divided by the average temperature rise across the combustor. This term is shown in figure 12 as a function of equivalence ratio for the various inlet conditions.

For low equivalence ratios some sections of the catalyst bed are more effective than others as shown by high values of the exit temperature uniformity term. Coinciding with good performance in other respects, the exit temperature became more uniform over the cross section as equivalence ratio was increased. Values of $(T_{\text{max}} - T_{\text{min}})/(T_{\text{avg}} - T_{\text{in}})$ near 0.1 or below were achieved for all inlet conditions. For a combustor temperature rise of 800 K, this value indicates a temperature spread of 80 K from the minimum to the maximum temperature.

The combustor pattern factor is defined as the difference between the maximum exit temperature and the average exit temperature divided by the average temperature rise across the combustor. It is always less than the uniformity factor of figure 12.

Minimum Operating Temperature

As noted previously, the catalytic reactor displays a sudden improvement in performance when a critical equivalence ratio (or exit temperature) is reached. Efficiency, for example, can rise from about 75 percent to virtually 100 percent over a narrow range of equivalence ratio. The equivalence ratio at which this occurs represents the minimum value at which it would be reasonable to operate the combustor. To define this value, an arbitrary efficiency level of 90 percent was chosen. The efficiency curves of figure 5 were used to determine the equivalence ratio at which 90 percent combustion efficiency was achieved for each inlet condition. The corresponding ideal adiabatic flame temperatures are shown in figure 13 as a function of reference velocity. In addition to suggesting a lower limit to good performance, this figure also indicates the effect of the inlet parameters on performance.

For given inlet temperature, pressure and equivalence ratio, the extent of reaction of the fuel depends directly on the residence time within the catalytic reactor; therefore, the minimum operating temperature increases linearly with reference velocity for the range of velocities tested. An increase in inlet temperature permits operation at a lower exit temperature without loss in performance; an increase in inlet pressure requires the exit temperature to be raised to maintain performance.

The effect of pressure is contrary to the trend shown in conventional combustors in which increases in pressure produce improvements in performance for constant reference velocity. In a catalytic

combustor fuel and air molecules must diffuse to the surface of the reactor before combustion can occur. The effect of an increase in pressure is to hinder mass diffusion. A diffusion-limited combustor would result in a greater effect of pressure than the experimental results show; apparently, then, in the present experimental situation, the rate of mass diffusion is of the same order of magnitude as the chemical reaction rate.

Durability

The reactor was tested for a total of nearly 20 hours with exit temperatures over 1000 K. Figure 14 shows approximately how the run time was divided among the different ranges of exit temperature.

Towards the end of the testing program it became apparent during the course of one day's testing that the minimum operating temperature was greater than expected for a given condition. To verify this effect several test conditions were repeated; these results are given in figure 15 and compared with some of the original data. The curves for the repeated tests are shifted to the left such that the minimum operating temperature now occurs at a reference velocity which is approximately 3.5 m/s less than the original value. Except for the data presented in figure 15, the results for run conditions tested after this effect became apparent have not been included in this report.

Several explanations can be considered for the fairly sudden change in performance noted in figure 15. Poisoning of the catalyst due to the presence of sulfur in the fuel could have occurred. Analysis of the fuel showed mercaptan sulfur of 114 ppm and sulfur in the form of H_2S of 392 ppm. However, the effect would be a gradual degradation if this were the cause. It is also possible that the catalyst could have eroded or vaporized away from the substrate material, but, again, a

sudden change would not be expected. Finally, a change in the composition of the fuel could have been responsible for the observed performance changes. Although the same supply of propane was used for all the testing reported here, it is possible that some of the impurities in the fuel which tend to settle out could have led to a change in the composition of the fuel introduced to the test section.

On completion of testing the combustor was removed for inspection. The appearance of the combustor is shown in figure 16. Some local nibbling of the substrate had occurred at the inlet face, and the bed was somewhat discolored from the exposure to high temperatures. A small piece (about 0.5 cm by 0.5 cm) of the reactor bed was found to have cracked off at the housing wall; otherwise the bed was intact.

CONCLUDING REMARKS

The results show that it is possible with a catalytic reactor to react fuel and air at realistic gas turbine combustor operating conditions and produce no measurable unburned hydrocarbons, less than 1 g CO/kg fuel, and total NO_x about two orders of magnitude less than conventional combustor levels. This can be achieved with combustor pressure loss of less than 4 percent for reference velocities around 23 m/s.

The operating range of the tested catalytic combustor was limited, however. Although the reaction does not become unstable or blow out, as would that in a premixed combustor, as the fuel-air mixture is made progressively leaner, the combustion efficiency and other performance parameters deteriorate rapidly. Thus, there is a minimum operating temperature for which reasonable performance can be expected. Tests were not conducted to determine the maximum exit temperature possible with the combustor; however, temperatures of about 2000 K would probably exceed the melting point of the uncooled ceramic substrate.

The catalytic combustor appears to be applicable to engines operating at fixed conditions, such as stationary power plants, providing the physical integrity and catalytic activity can be maintained for a reasonable length of time. It will have to be shown that damage to the turbine blades from pieces of broken substrate is unlikely. For applications involving variable inlet conditions, some form of variable geometry with bypass dilution air would appear to be required. Regardless of the use, development of a fuel/air premixing and pre-vaporizing system is necessary for successful operation of the catalytic combustor.

The results in this report were obtained with a particular proprietary catalyst and substrate provided by a single manufacturer and may not be typical of other catalytic or substrate materials or surface conditions.

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TABLE I. - TEST CONDITIONS

Inlet temperature, K	Inlet pressure, atm	Reference velocity, m/s	Airflow rate, kg/s
600	3	11	0.23
600	3	17	.35
600	6	9	.35
700	6	13	.44
800	3	23	.35
↓	3	30	.44
	6	12	.35
	6	15	.44
	6	18	.53

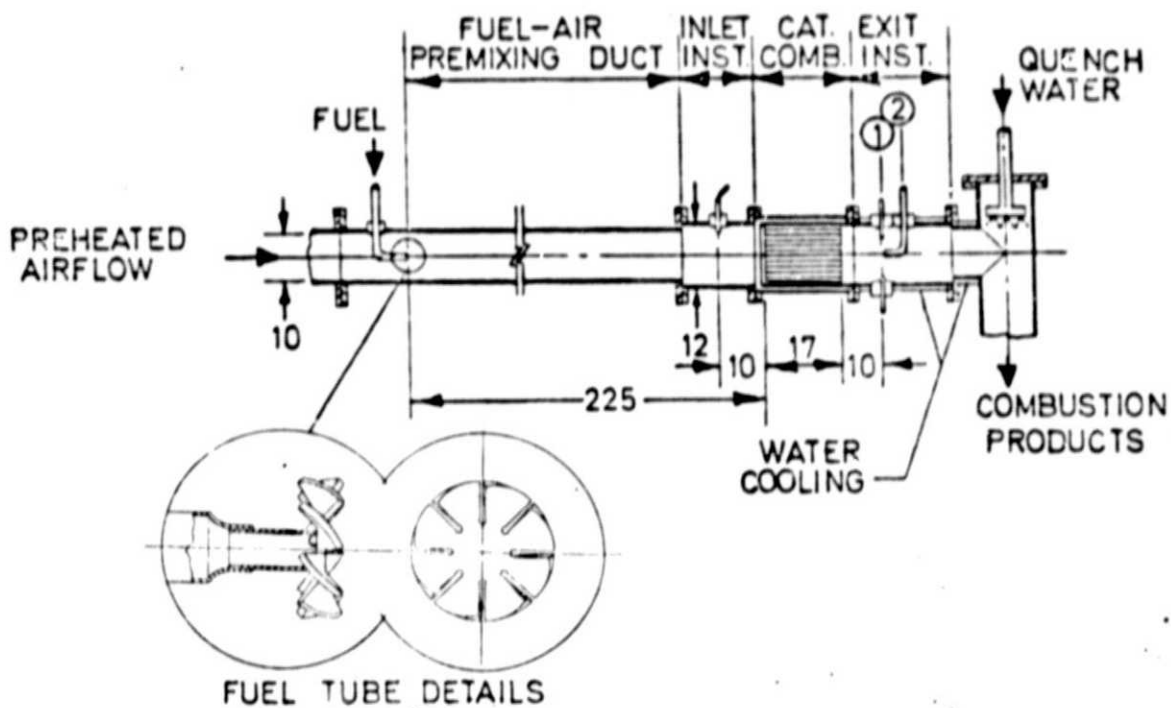
TABLE II. - PROPERTIES OF COMMERCIAL
GRADE PROPANE USED IN THIS STUDYAnalysis: C_3H_8 92 percent C_2H_4 1-2 C_3H_6 4-6 C_4H_{10} 1-2Volatile S 4-6 grains/100 ft³

Dew point: 244 K

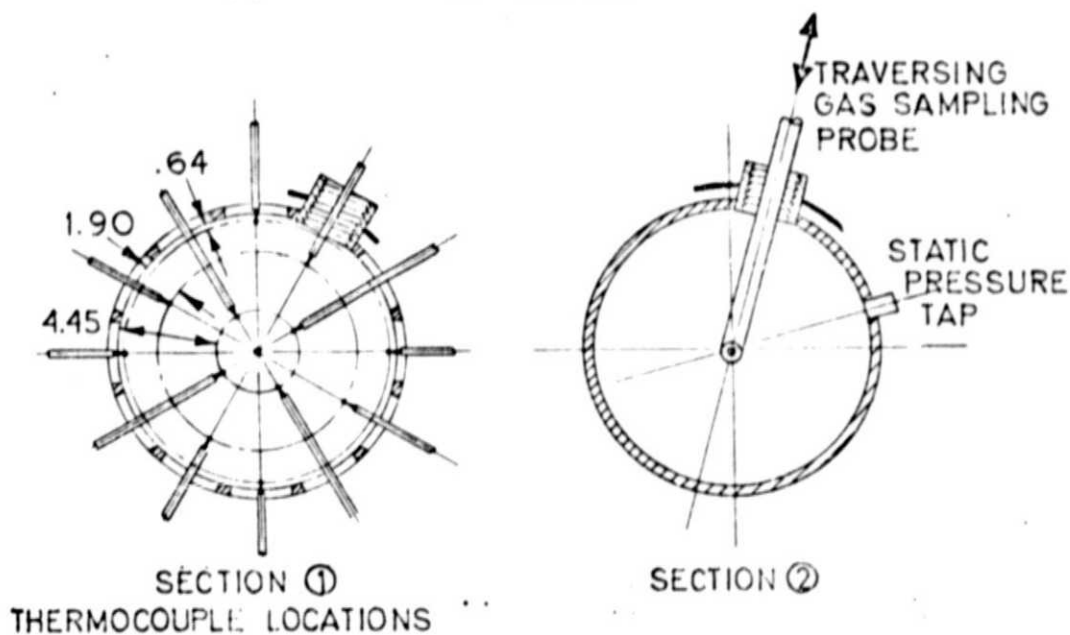
Heat content: 11 900 cal/g

Vapor pressure: 11.9 atm at 310 K

Specific gravity: 0.508



(a) GENERAL RIG DETAILS



(b) EXIT INSTRUMENTATION (LOOKING DOWNSTREAM)

FIGURE 1.—TEST RIG (DIMENSIONS ARE IN CM)

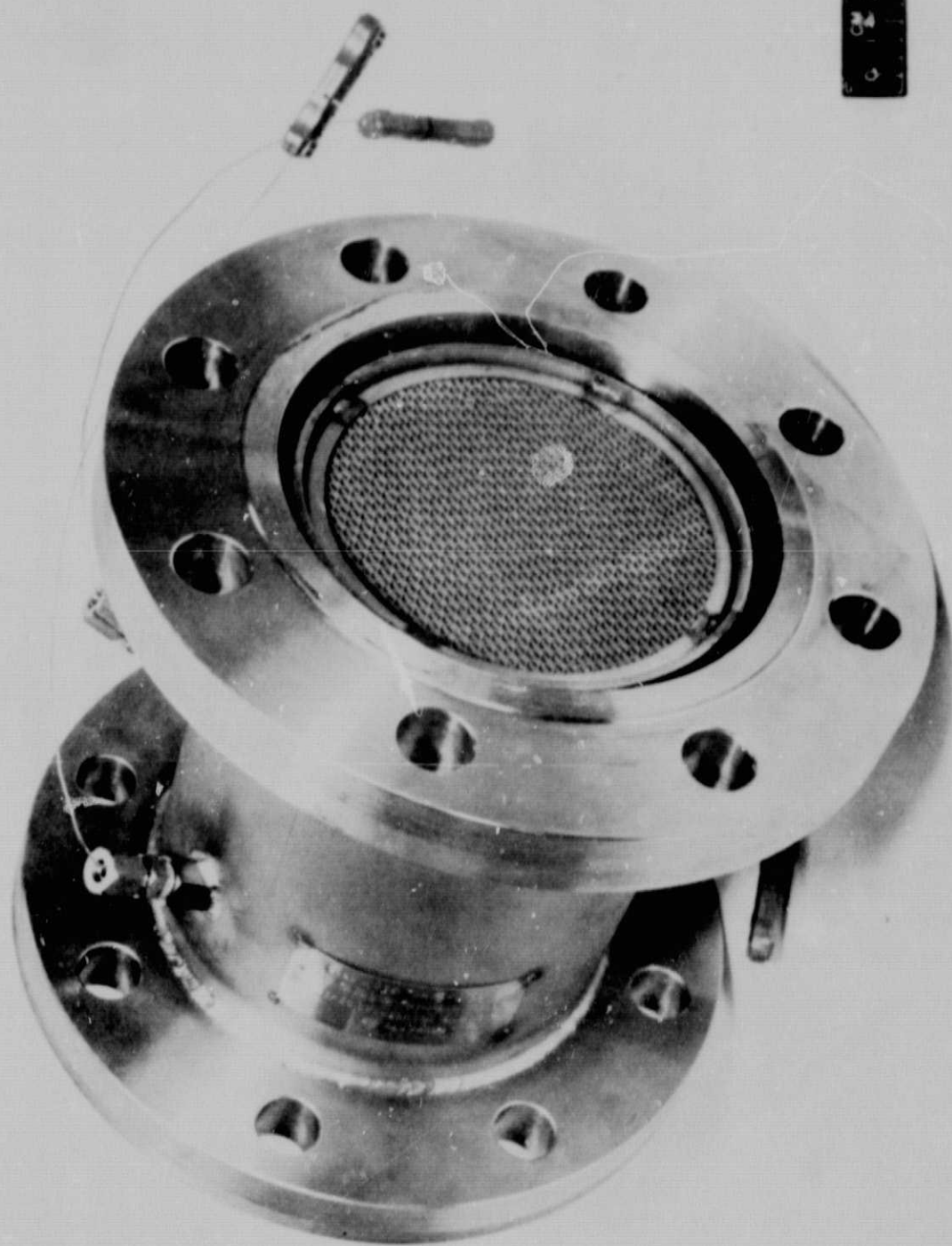


Figure 2.-Catalytic Reactor

(a) Inlet View

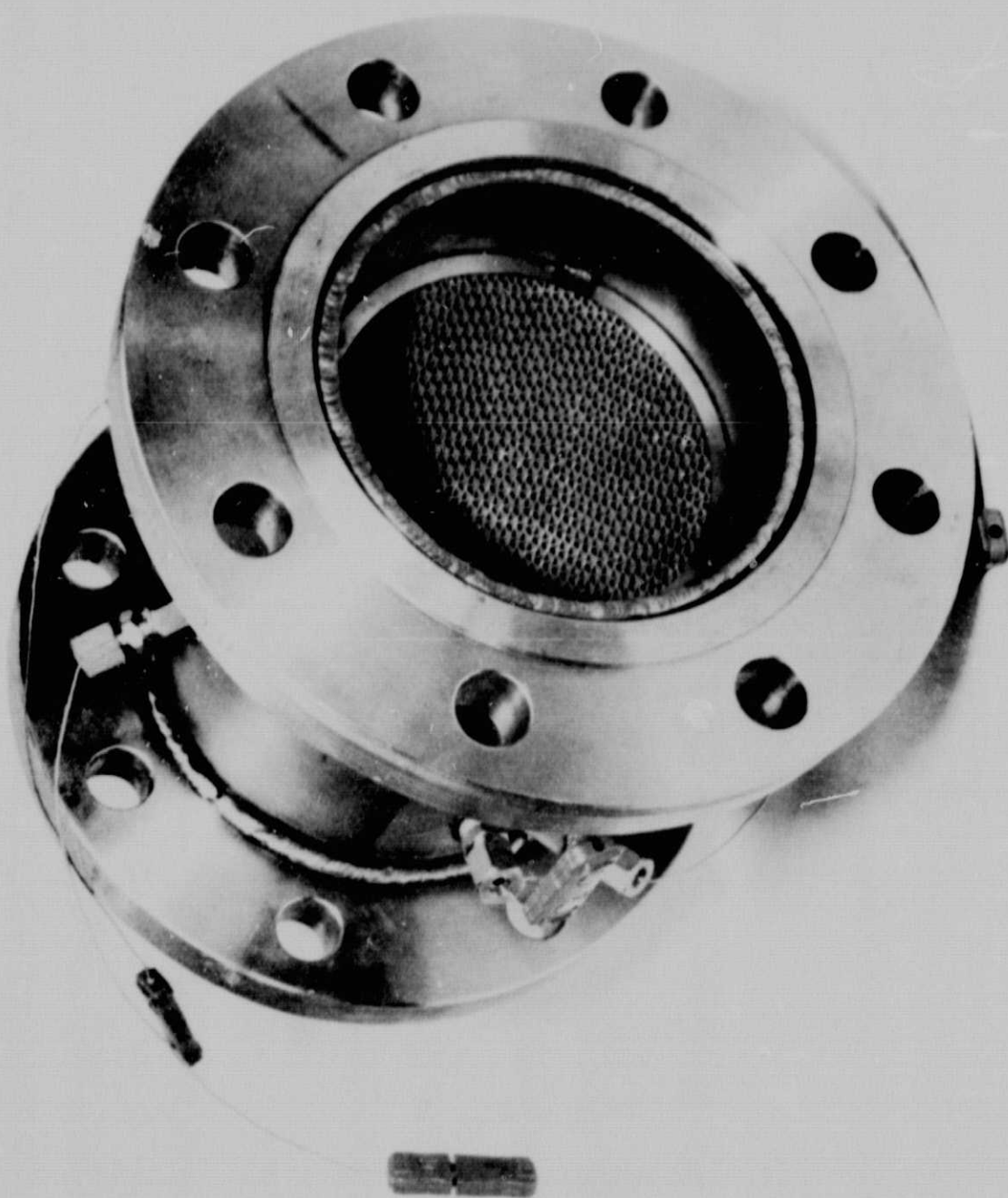


Figure 2.- (Concluded)

(b) Exit View

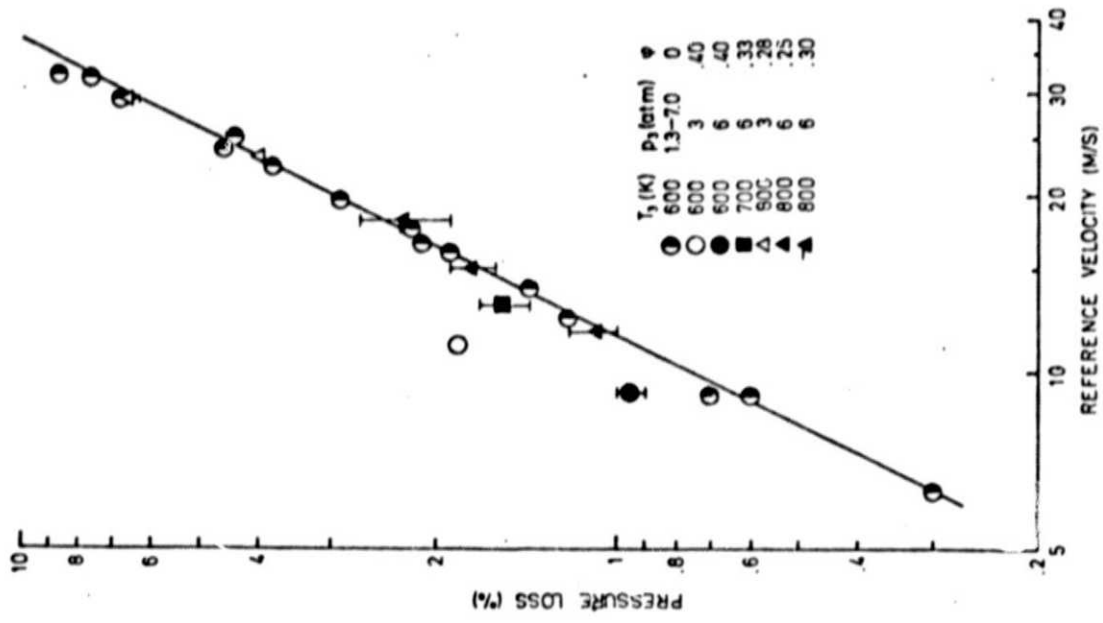
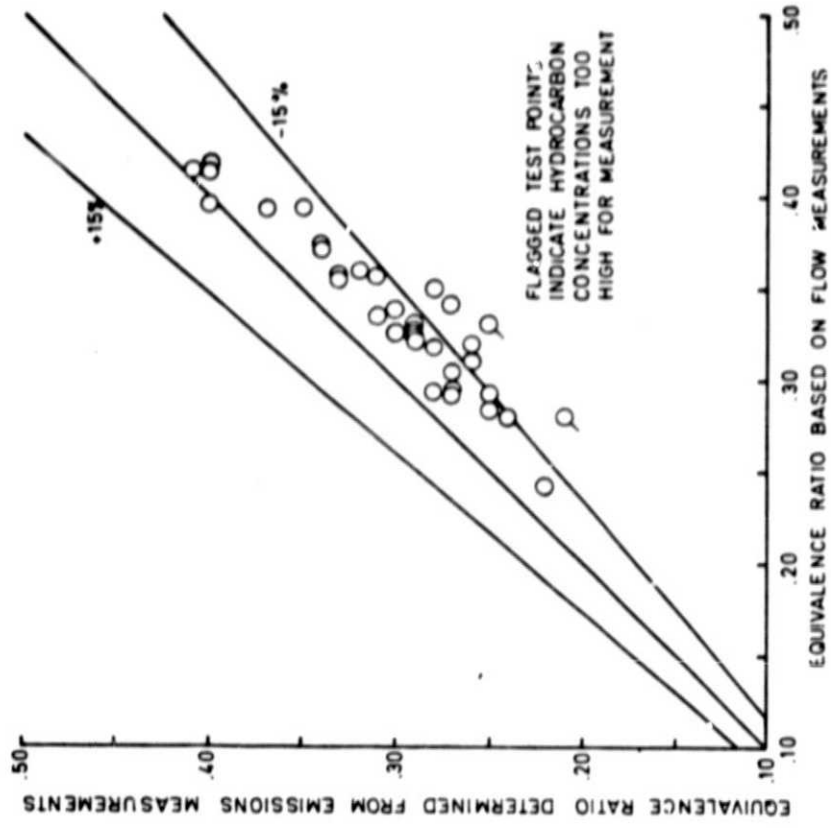


Figure 3.-Combustor Pressure Loss.



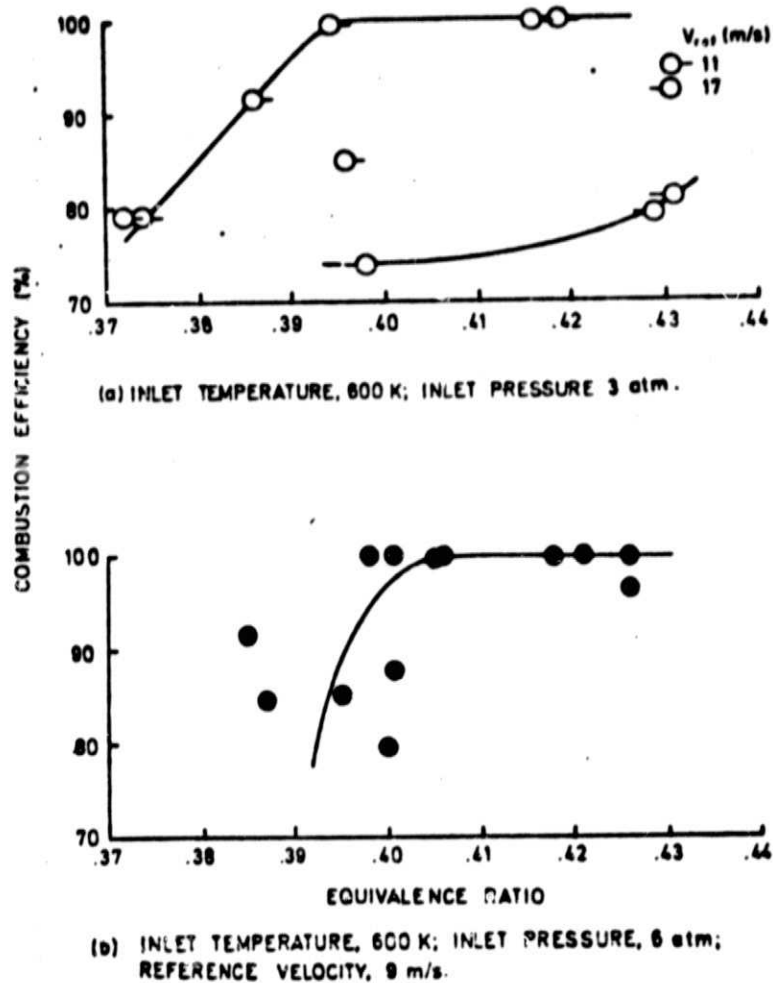
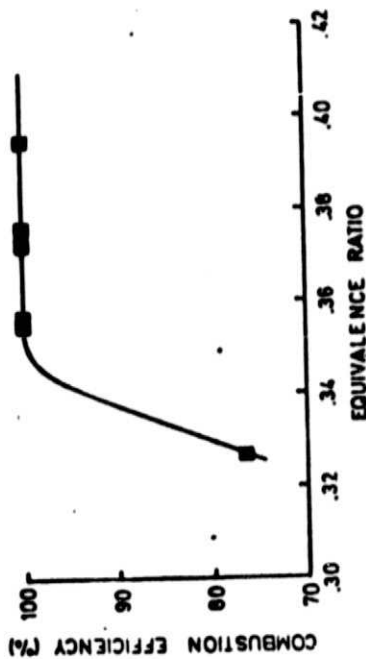


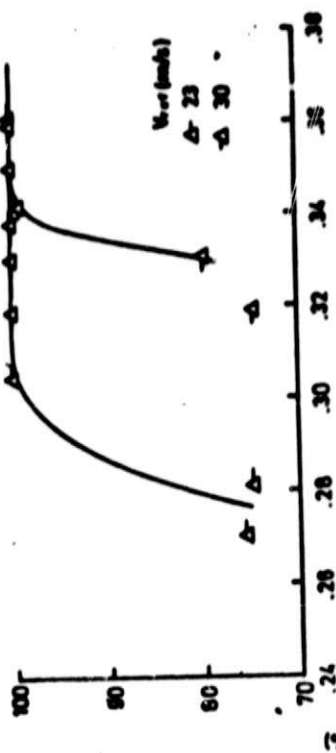
Figure 5.-Combustion Efficiency Determined from Exhaust Gas Analysis.

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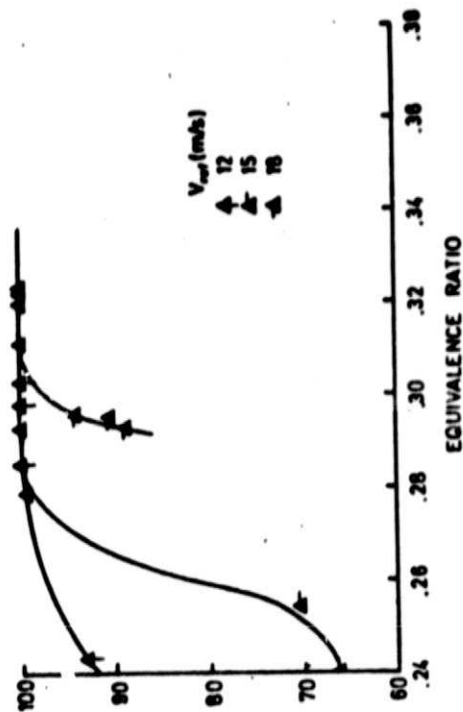
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(c) INLET TEMPERATURE, 700 K; INLET PRESSURE, 6 atm;
REFERENCE VELOCITY, 13 m/s.

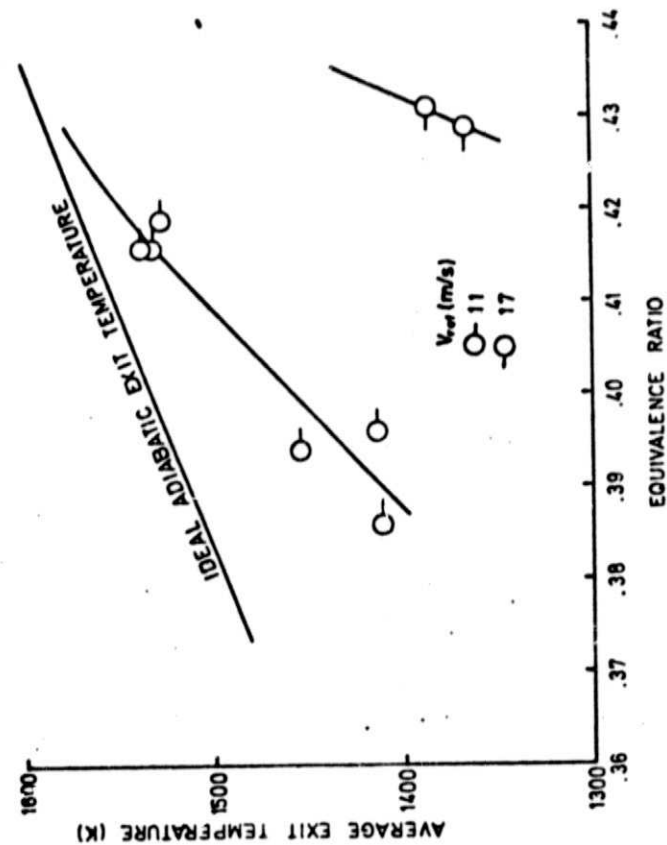


(d) INLET TEMPERATURE, 800 K; INLET PRESSURE, 3 atm.

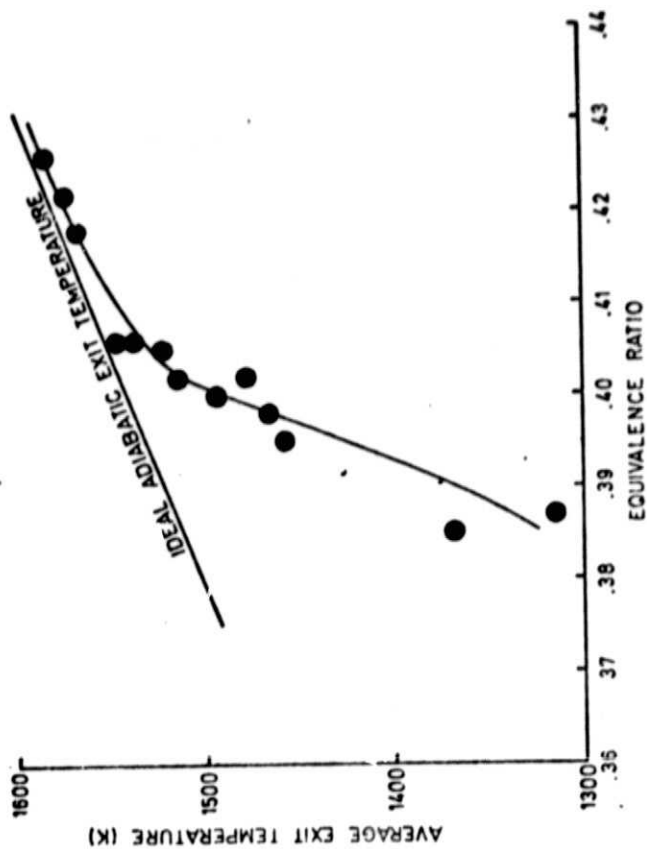


(e) INLET TEMPERATURE, 800 K; INLET PRESSURE, 6 atm

Figure 5.-(Concluded).

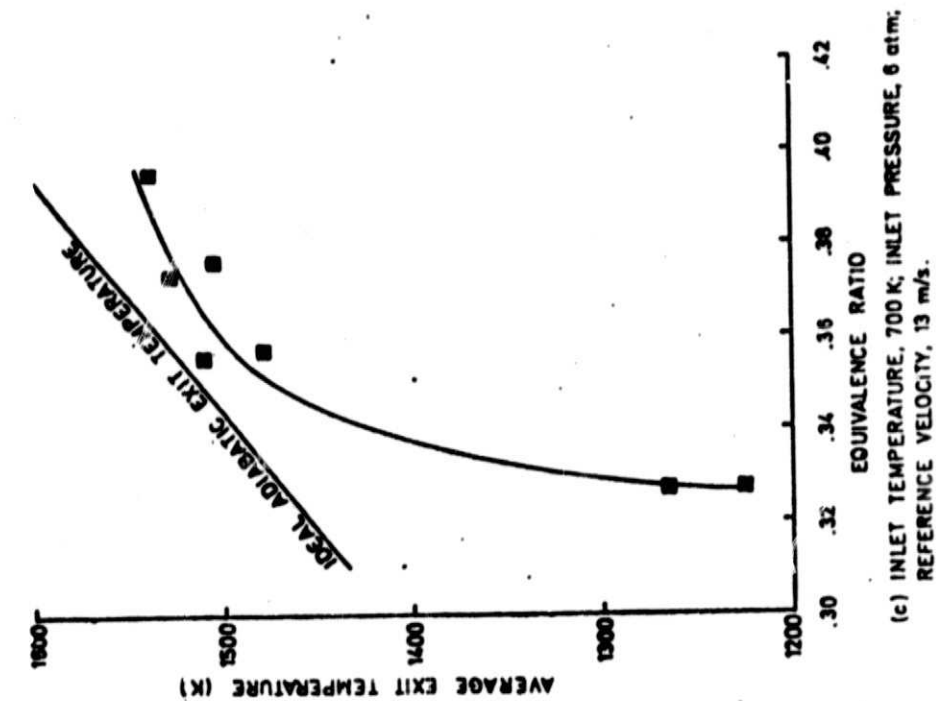


(g) INLET TEMPERATURE, 600 K; INLET PRESSURE, 3 atm.

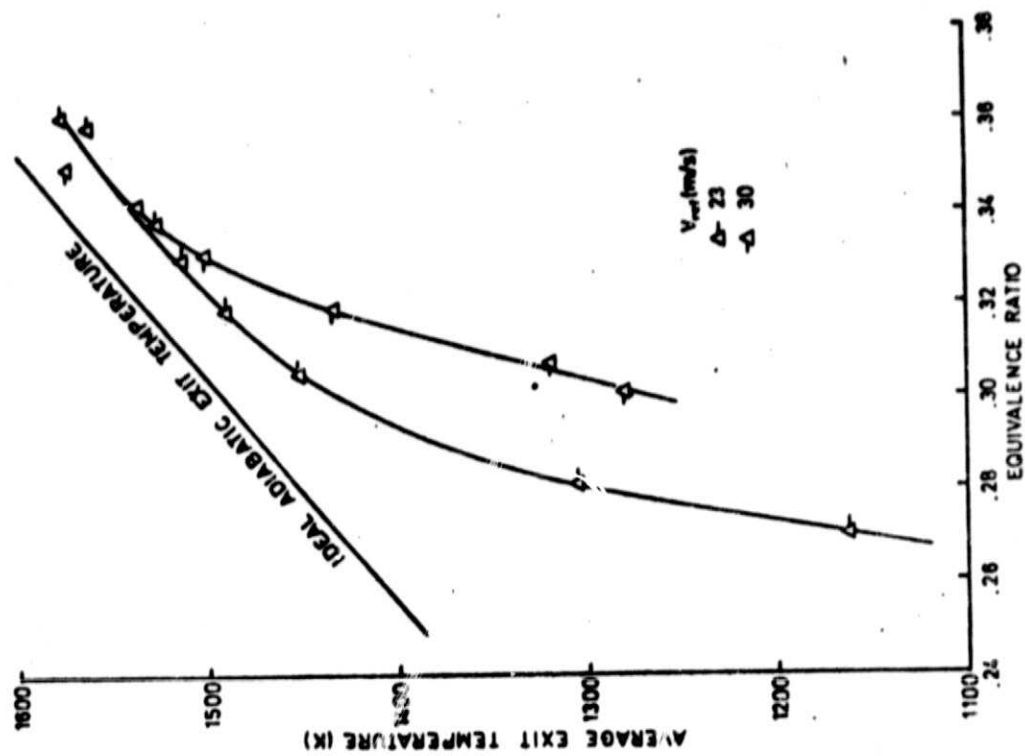


(b) INLET TEMPERATURE, 600 K; INLET PRESSURE, 6 atm; REFERENCE VELOCITY, 9 m/s.

Figure 6.-Combustor Temperature response.

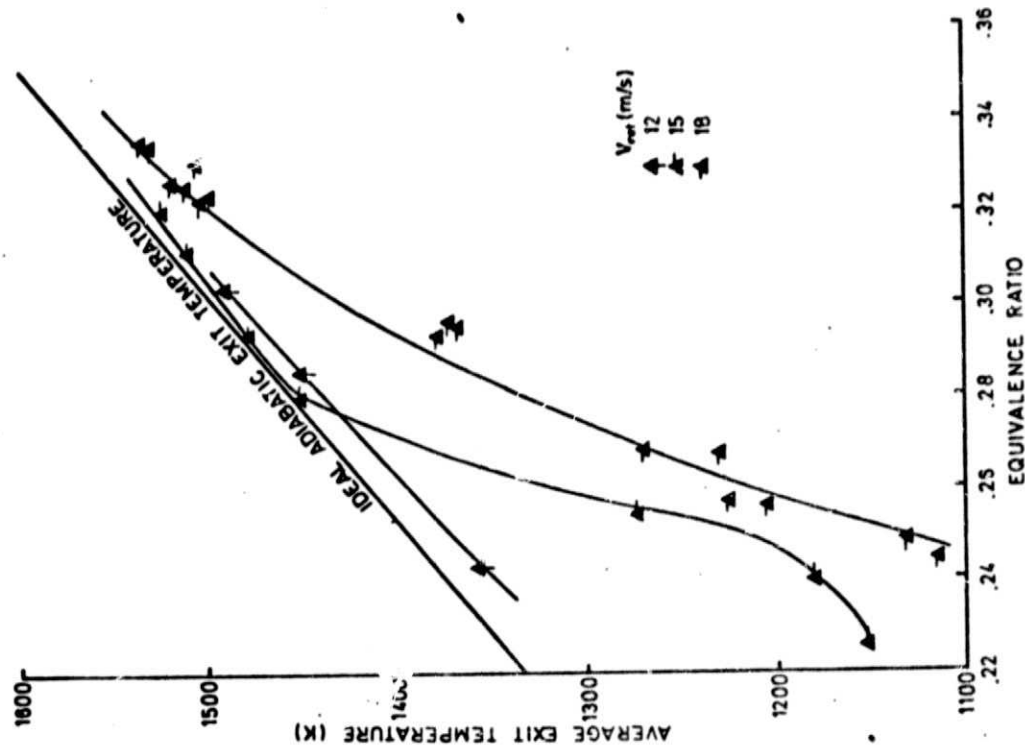


(c) INLET TEMPERATURE, 700 K; INLET PRESSURE, 6 atm; REFERENCE VELOCITY, 13 m/s.



(d) INLET TEMPERATURE, 800 K; INLET PRESSURE, 3 atm.

Figure 6.-(Continued).



(a) INLET TEMPERATURE, 800 K; INLET PRESSURE, 6 atm

Figure 6.- (Concluded).

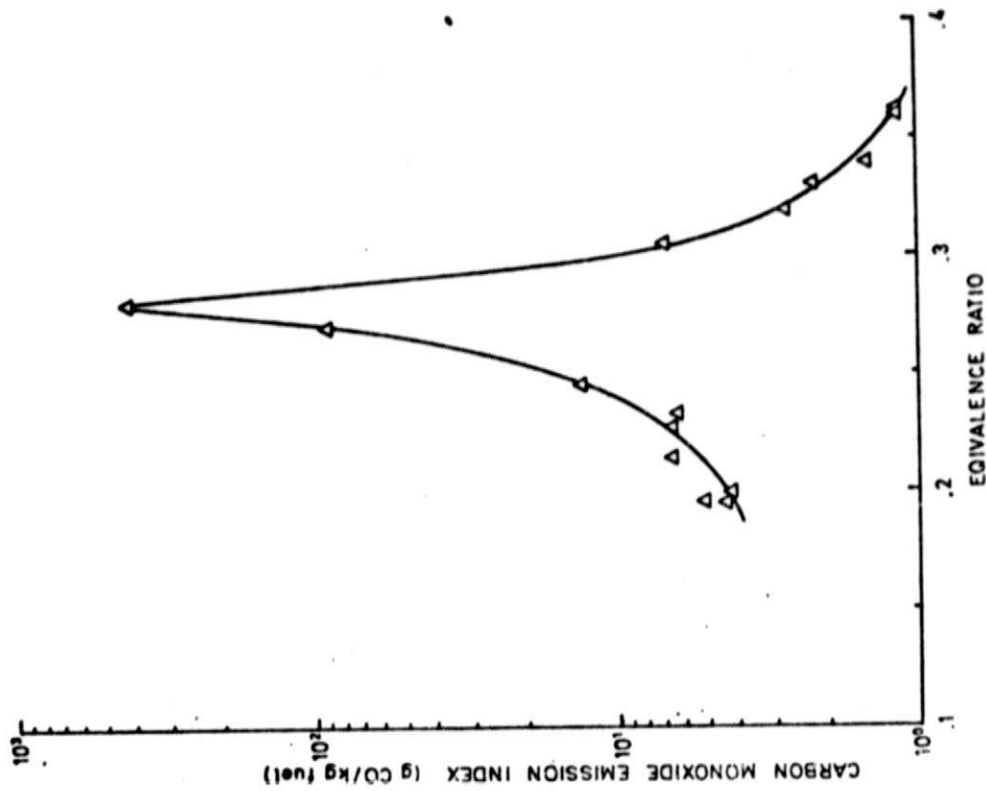
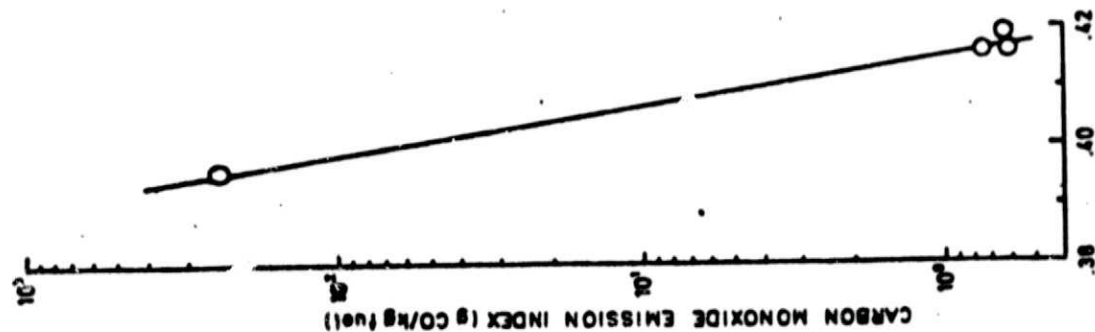
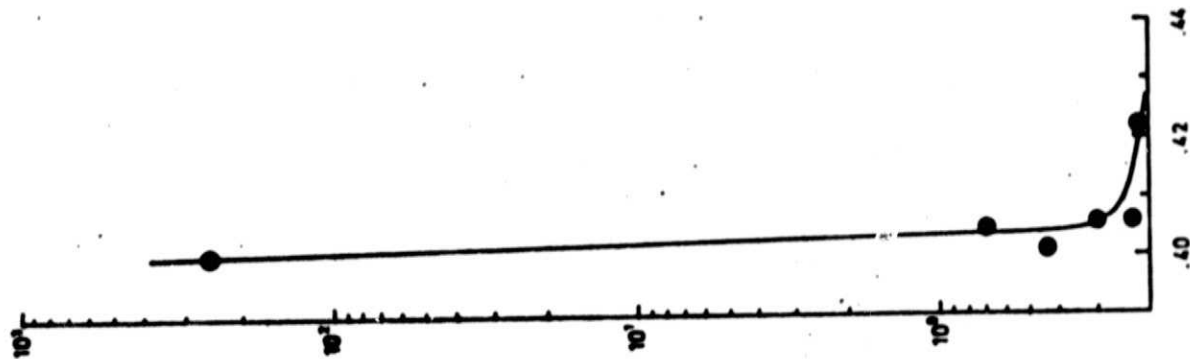


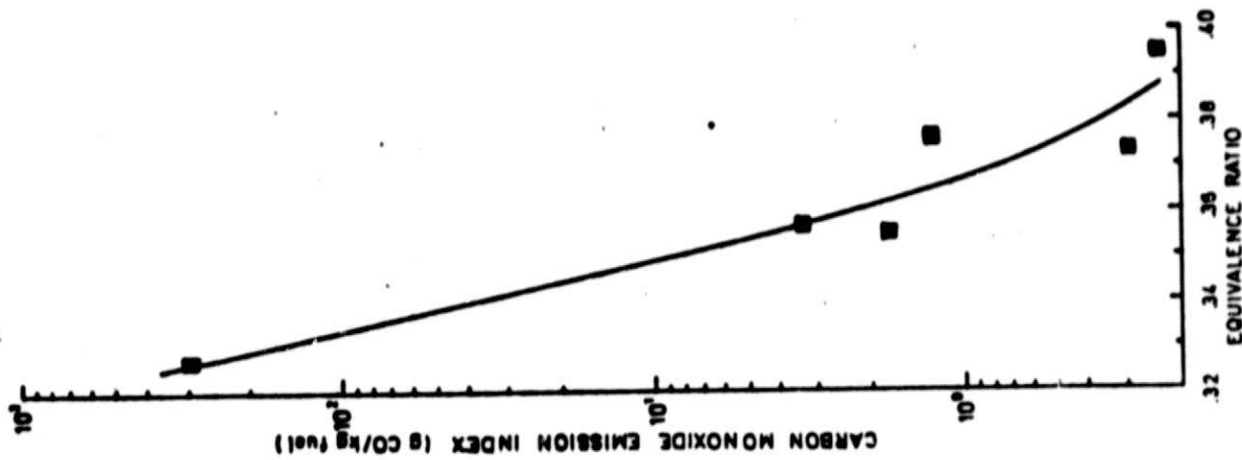
FIGURE 7.- TYPICAL CARBON MONOXIDE EMISSION RESPONSE.
INLET TEMPERATURE, 800 K; INLET PRESSURE, 3 atm,
REFERENCE VELOCITY, 23 m/s.



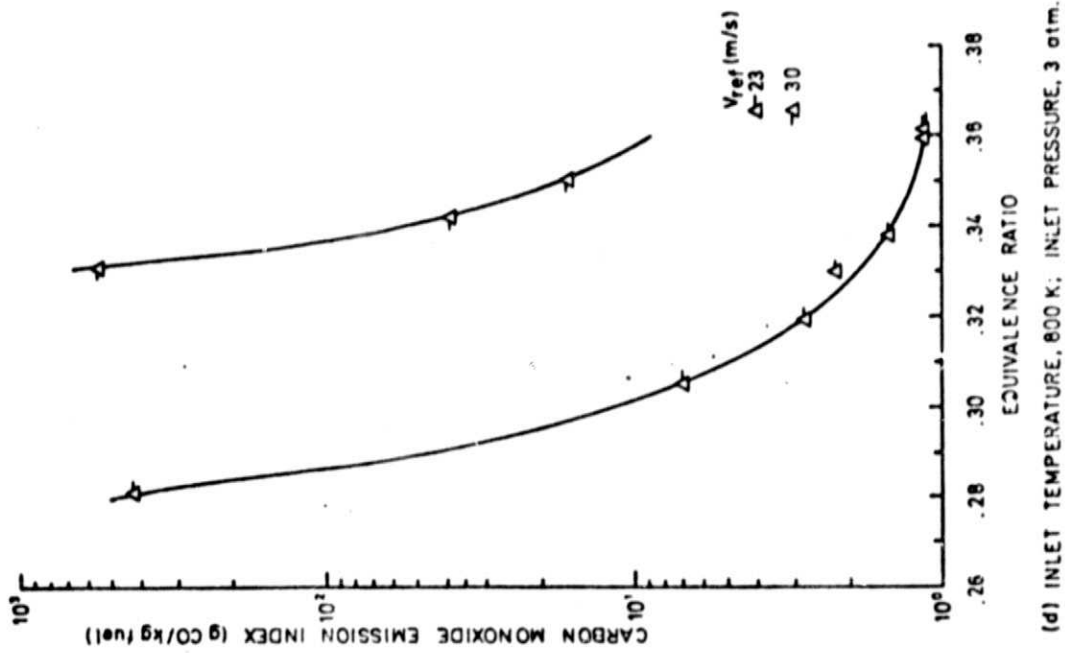
(a) INLET TEMPERATURE, 800 K;
INLET PRESSURE, 3 atm;
Reference Velocity, 11 m/s.



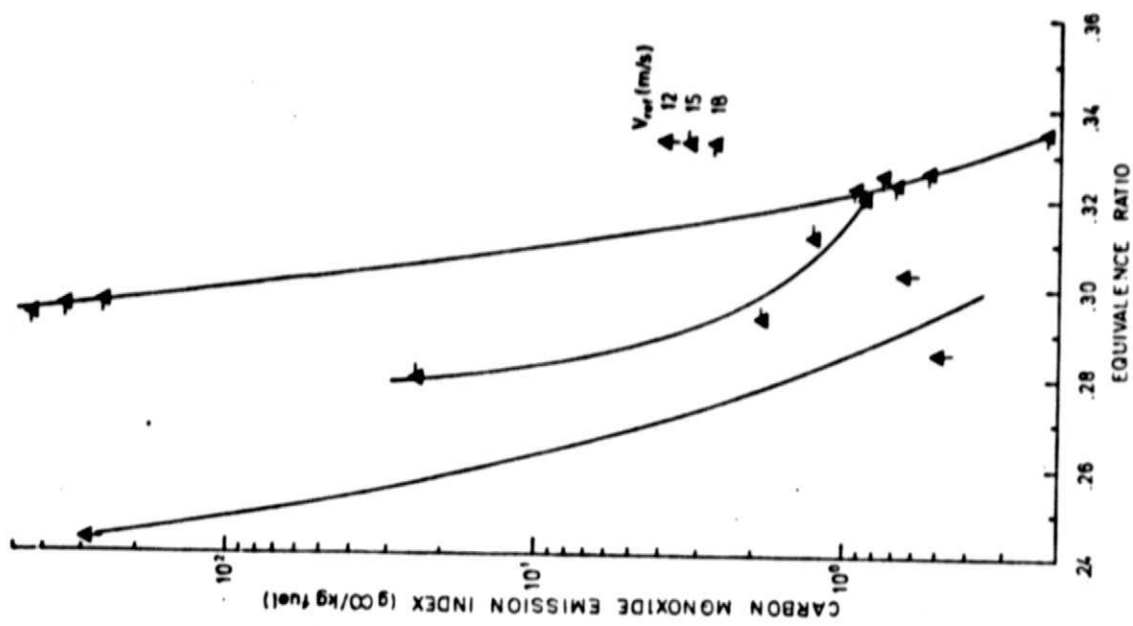
(b) INLET TEMPERATURE, 600 K;
INLET PRESSURE, 6 atm;
Reference Velocity, 9 m/s.



(c) INLET TEMPERATURE, 700 K; INLET PRESSURE, 6 atm;
Reference Velocity, 13 m/s.



(d) INLET TEMPERATURE, 800 K; INLET PRESSURE, 3 atm.



(e) INLET TEMPERATURE, 800 K; INLET PRESSURE, 6 atm

Figure 8.--(Concluded).

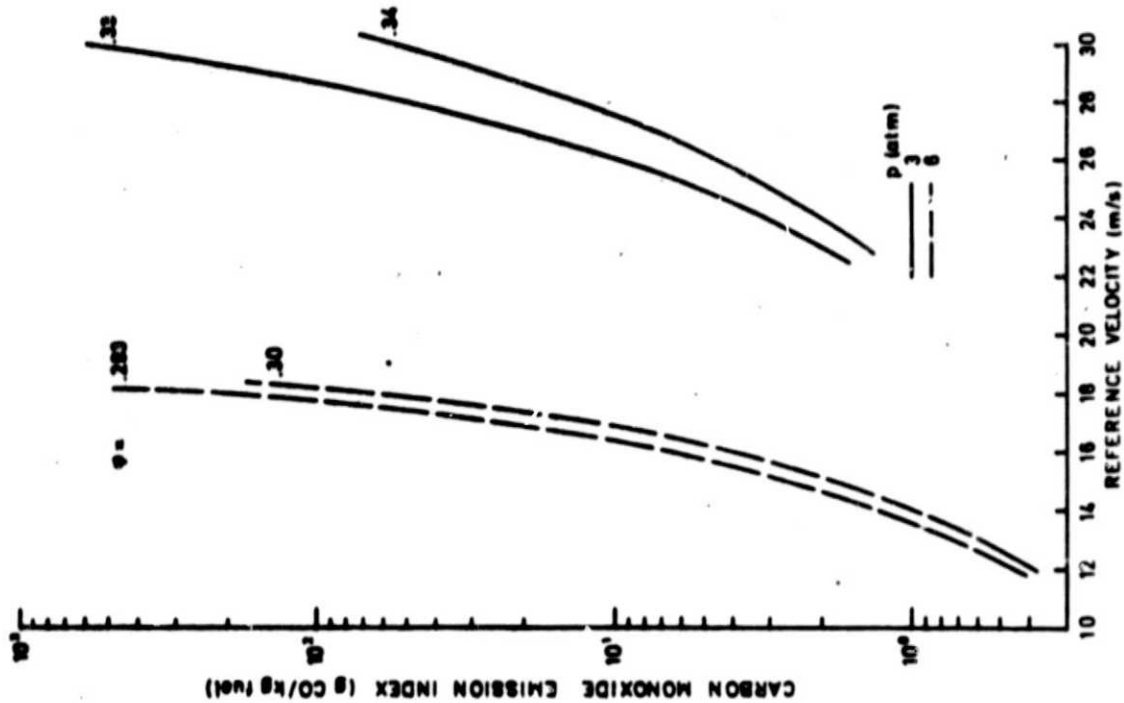
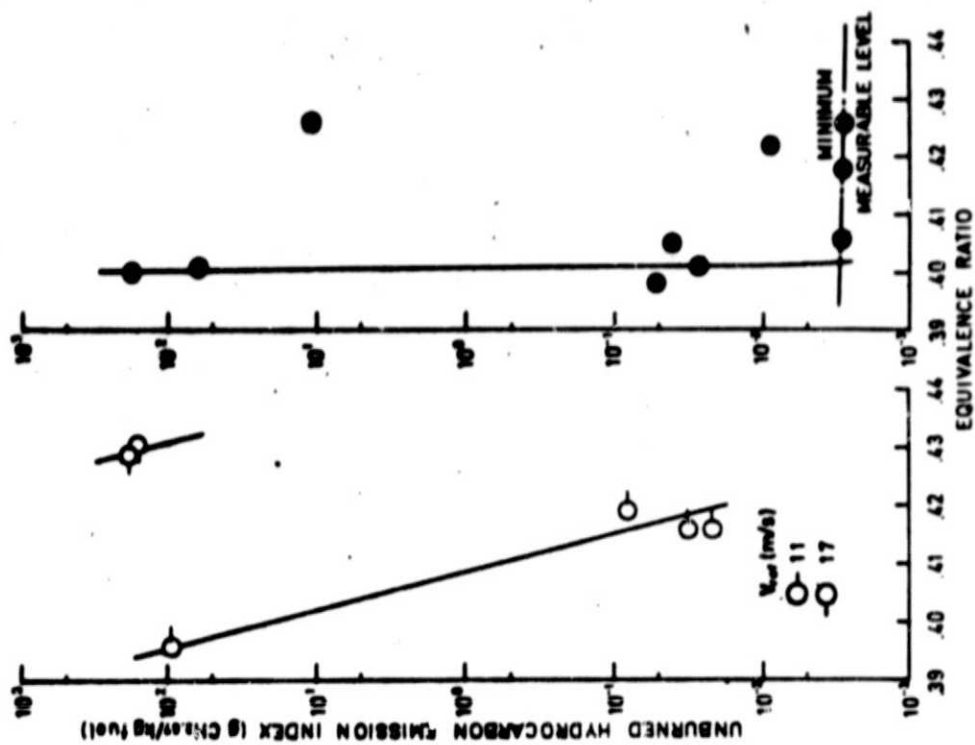
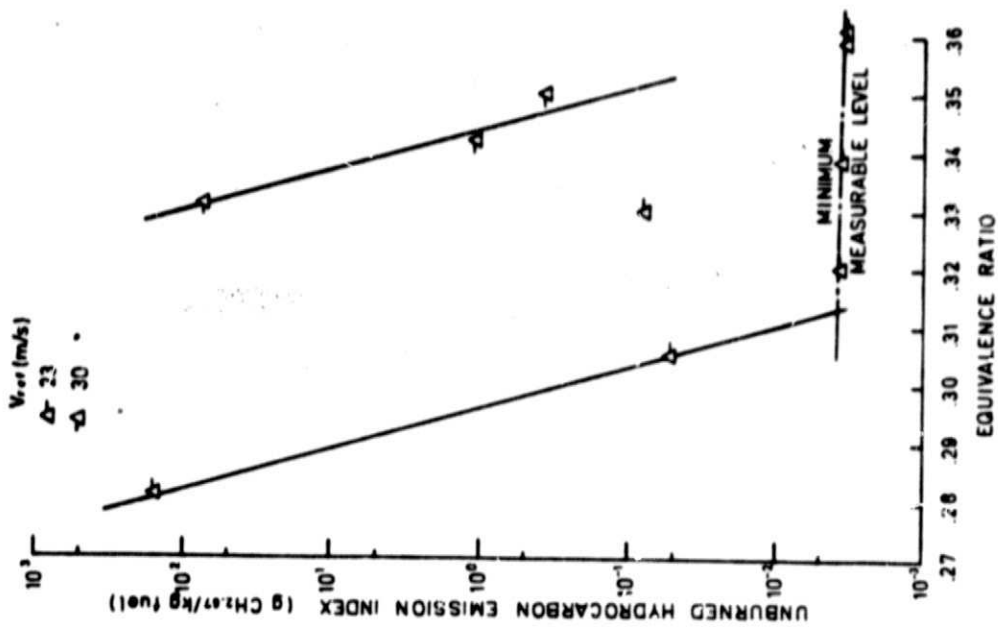


FIGURE 9.-EFFECT OF REFERENCE VELOCITY ON CARBON MONOXIDE EMISSIONS. CROSS PLOT OF DATA FROM FIGURE 8. INLET TEMPERATURE, 800 K.



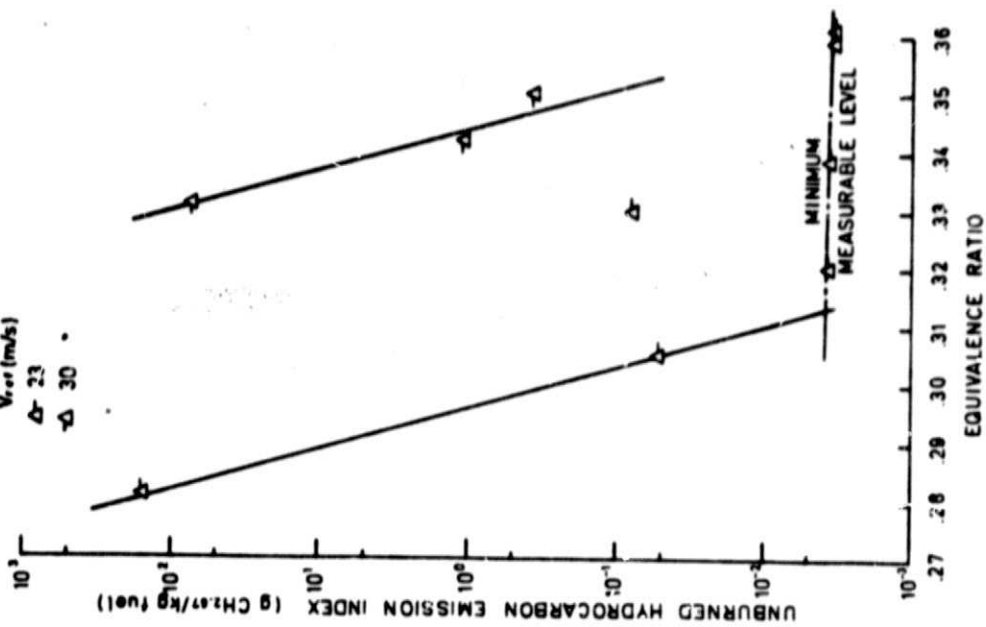
(a) INLET TEMPERATURE, 600 K; INLET PRESSURE, 3 atm; REFERENCE VELOCITY, 9 m/s.
(b) INLET TEMPERATURE, 600 K; INLET PRESSURE, 6 atm; REFERENCE VELOCITY, 9 m/s.

Figure 10.-Emissions of Unburned Hydrocarbons.



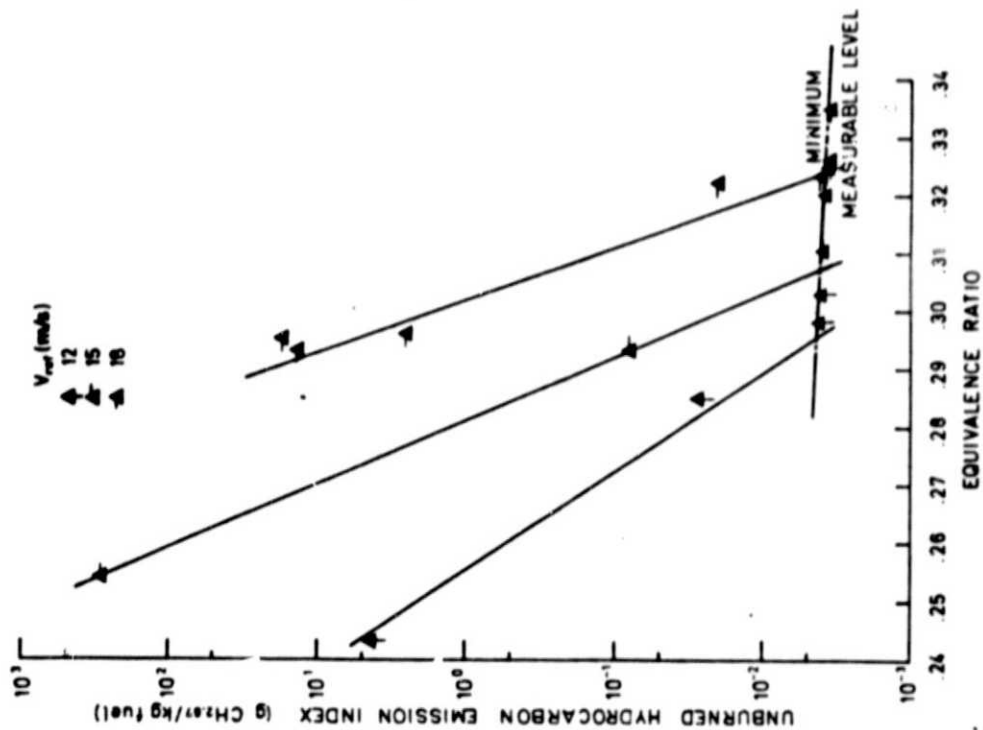
(c) INLET TEMPERATURE, 700 K; INLET PRESSURE, 6 atm;
REFERENCE VELOCITY, 13 m/s.

V_{ref} (m/s)
 Δ 23
 Δ 30



(d) INLET TEMPERATURE, 800 K; INLET PRESSURE, 3 atm.

Figure 10. (Continued).



(e) INLET TEMPERATURE, 800 K; INLET PRESSURE, 6 atm

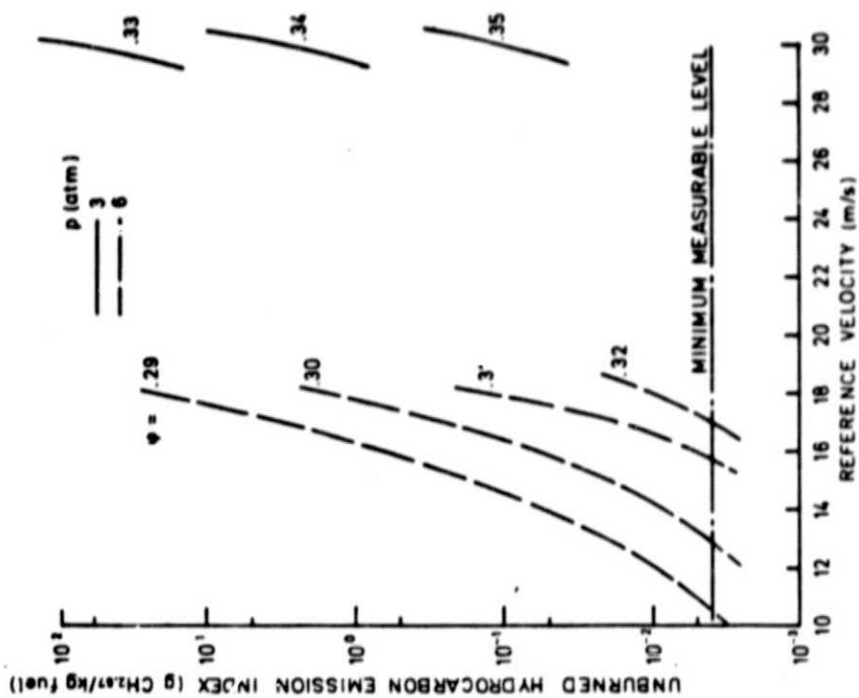


FIGURE 11.-EFFECT OF REFERENCE VELOCITY ON EMISSIONS OF UNBURNED HYDROCARBONS. CROSS PLOT OF DATA FROM FIGURE 10. INLET TEMPERATURE, 800 K.

Figure 10.-(Concluded).

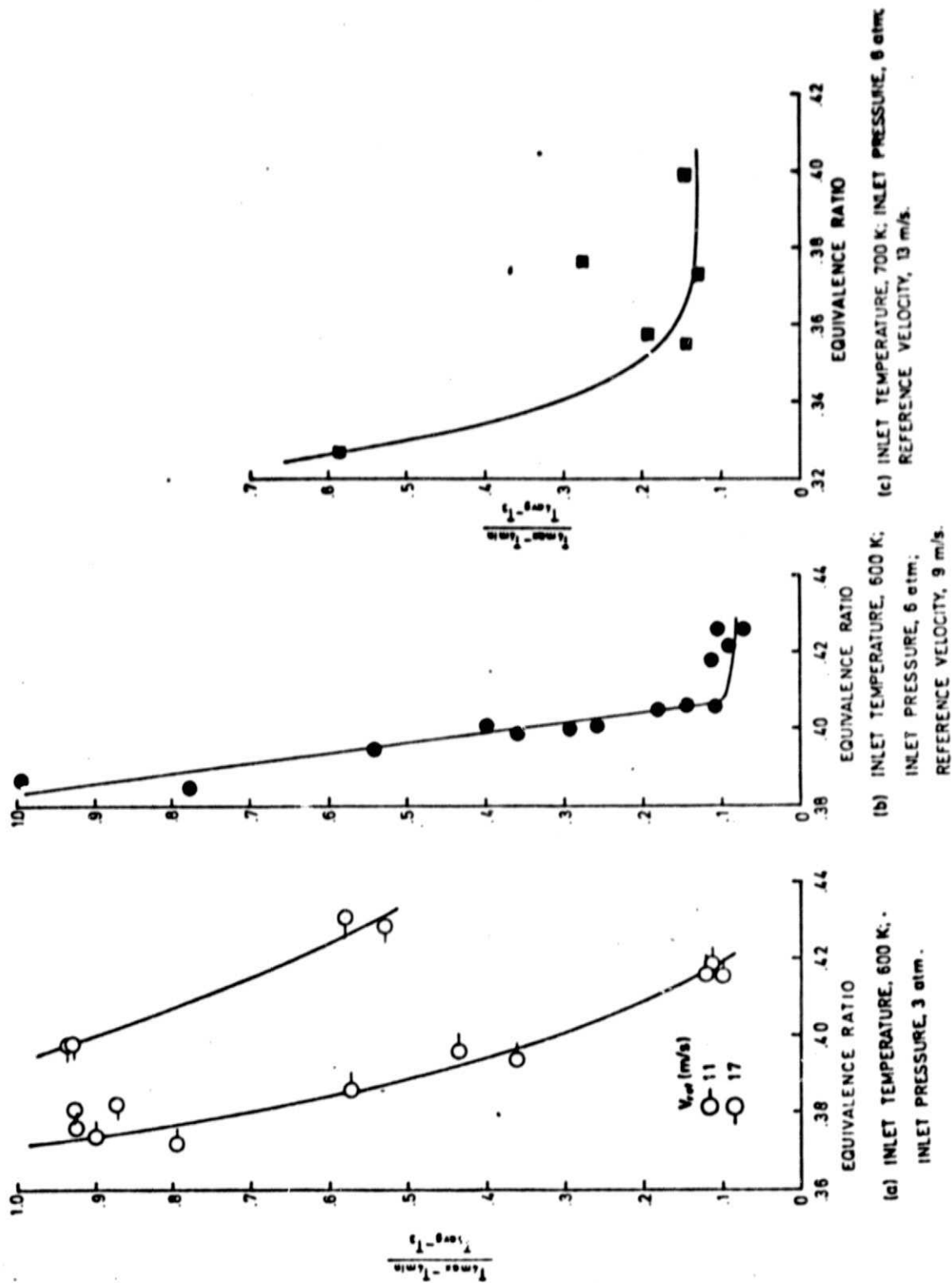
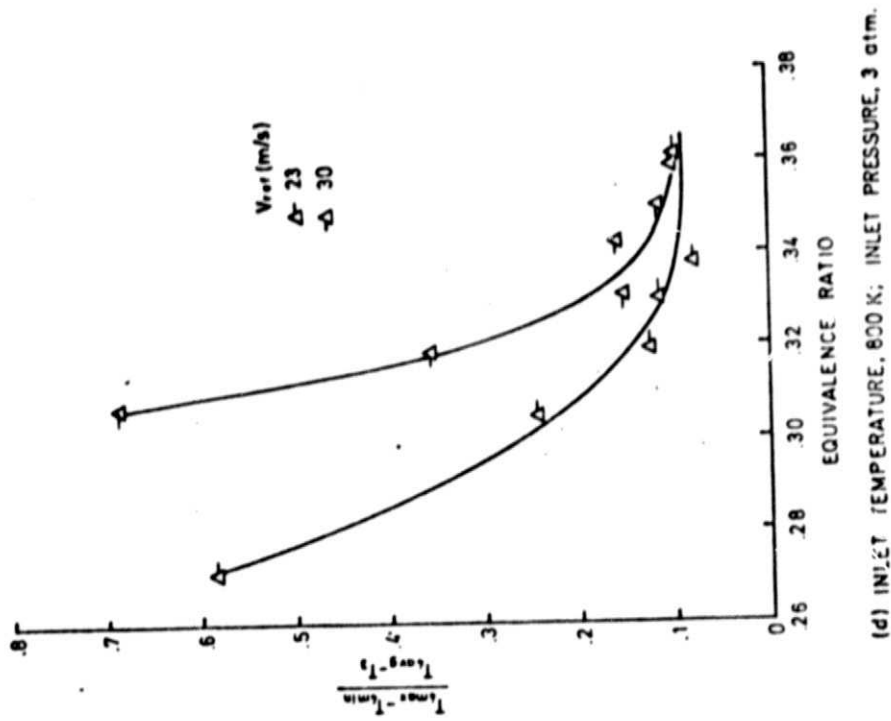
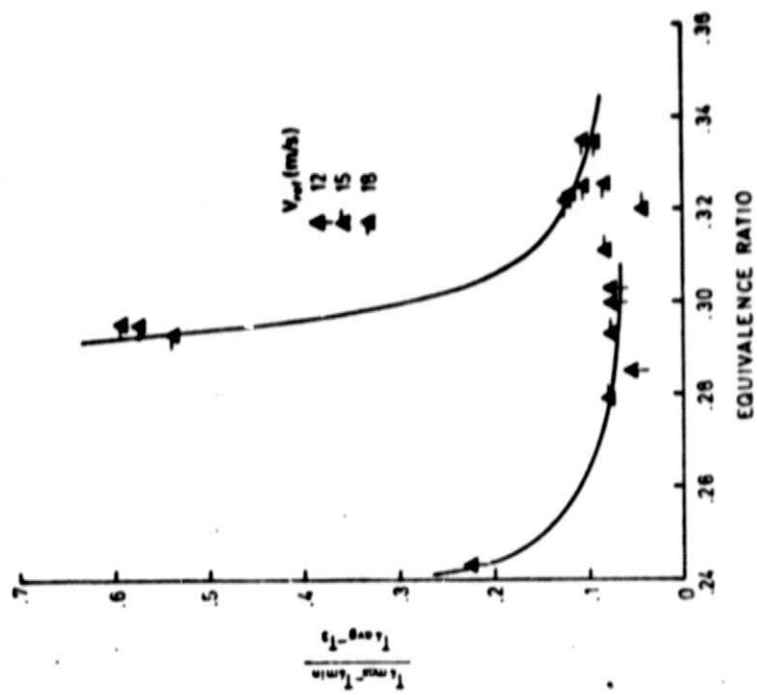


Figure 12.-Exit Temperature Uniformity.



(d) INLET TEMPERATURE, 800 K; INLET PRESSURE, 3 atm.



(e) INLET TEMPERATURE, 800 K; INLET PRESSURE, 6 atm

Figure 12.--(Concluded).

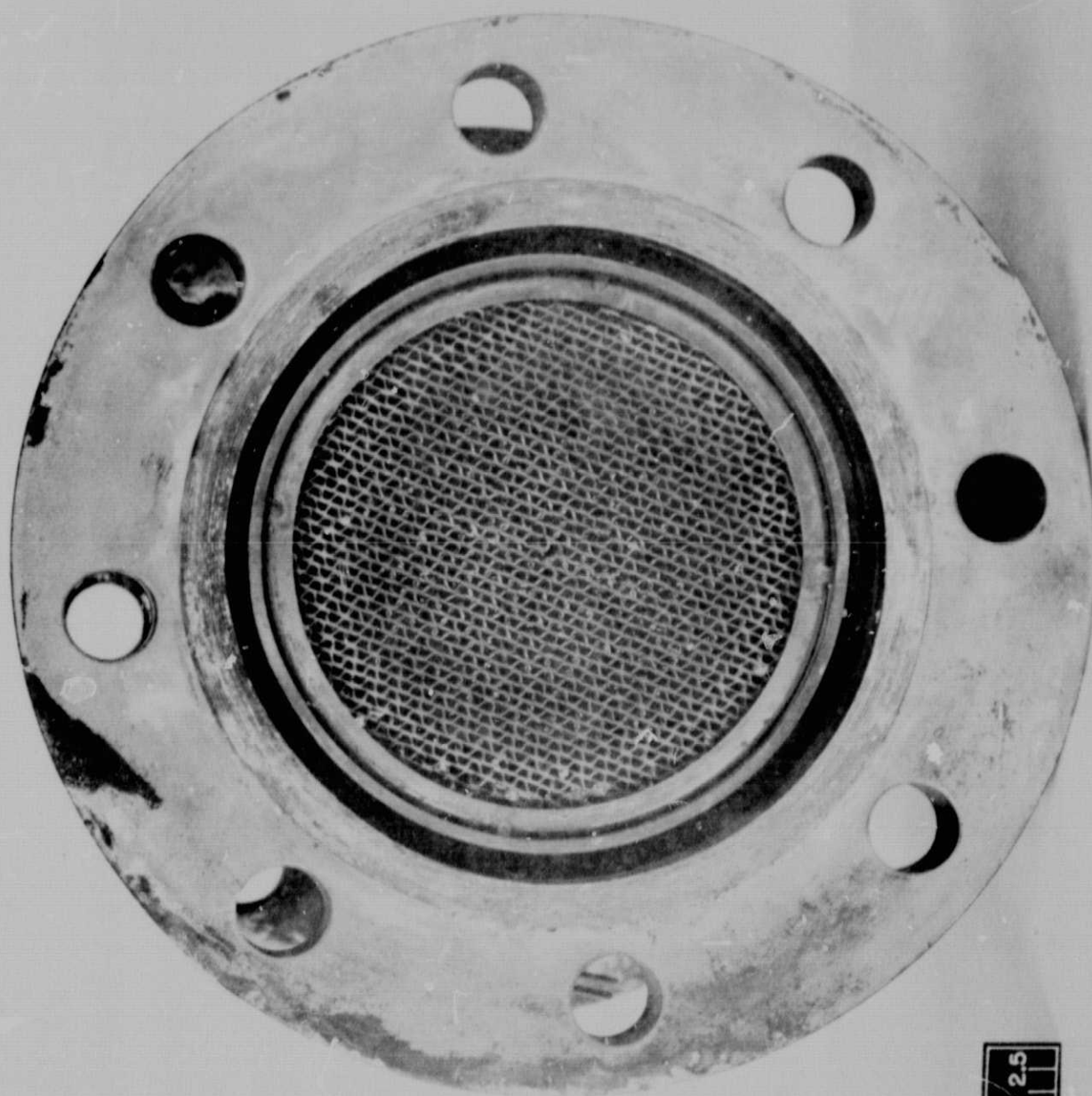


Figure 16.-Reactor Condition at
Completion of Testing.

(a) Inlet View

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OF POOR QUALITY.

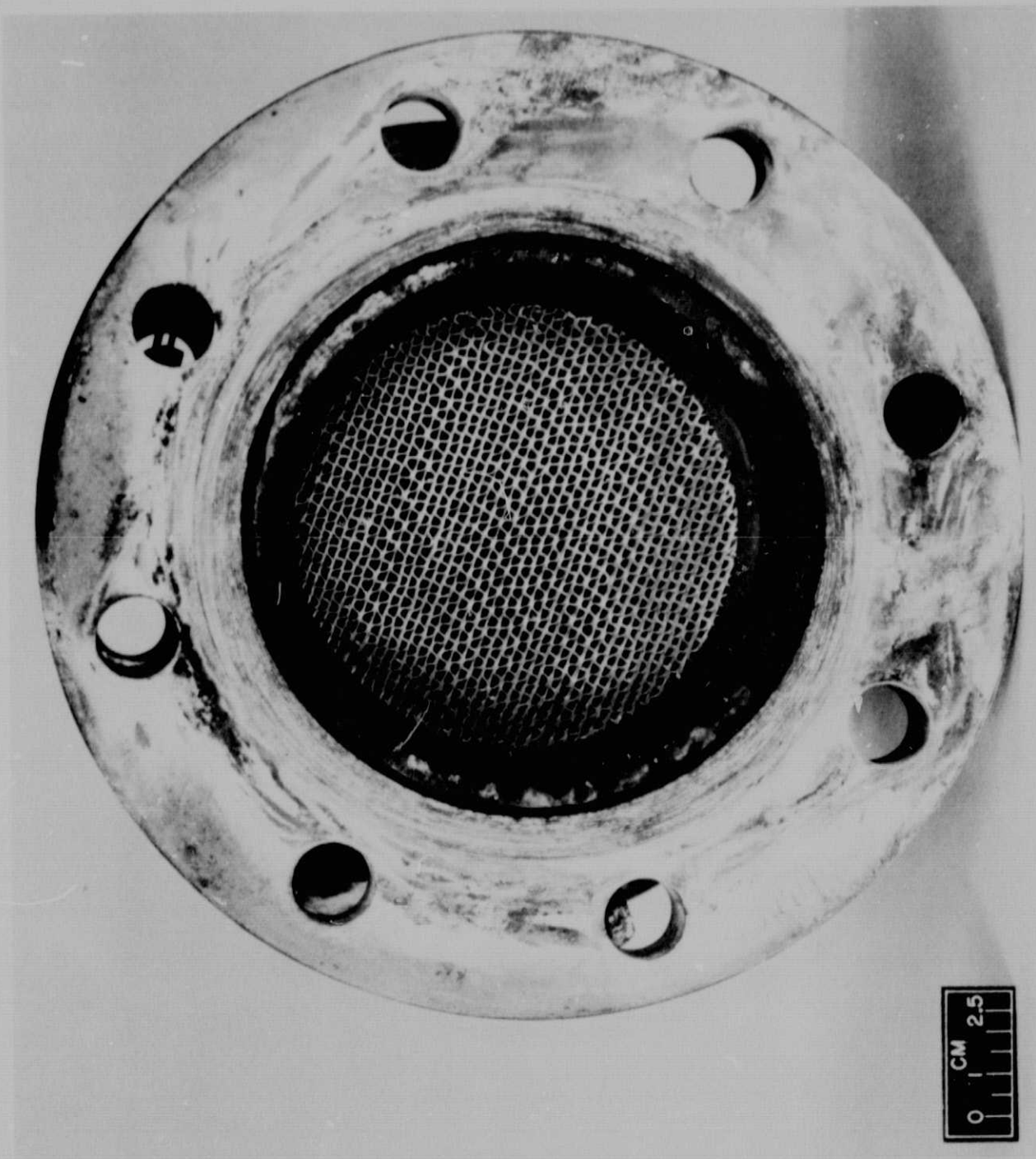


Figure 16.--(6oncluded)

(b) Exit View